COMPARISON OF THE ECOPROFILES OF SUPERCONDUCTING AND CONVENTIONAL 25 MVA TRANSFORMERS USING THE LIFE CYCLE ASSESSMENT METHODOLOGY

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ABSTRACT

A Life Cycle Assessment (LCA) study, according to ISO 14040 Standards, was carried out with the aim to compare the environmental performances of three 25 MVA transformers with different manufacturing characteristics:

- a high temperature superconducting (HTS) transformer with first generation (1G) BSCCO tape windings,
- a HTS transformer with second generation (2G) YBCO coated conductors windings,
- a conventional paper-oil insulated transformer with copper windings.

A “from cradle to grave” approach was used for the comparative LCA. This paper reports the results of LCA with the identification of the most environmental-friendly solution and the critical issues in the environmental profiles for the three different types of power transformers.

INTRODUCTION

Power transformers, the heart of the electrical network, are reliable and efficient devices, often operating at efficiencies as high as 99% at full load. However, they lose a significant amount of energy during their service life, due to the combination of load losses associated with the eddy current and hysteresis of the magnetic core and no-load losses caused by the Joule effect in the electrical windings. The energy production, to compensate for these losses, causes environmental impacts owing to the emissions of polluting substances and greenhouse gases, especially CO₂, which contribute to the planet climate changes. To reduce the load losses, the copper windings of the transformer could be replaced by innovative conductor based on High Temperature Superconductors (HTS).

1st and 2nd generation HTS are available in long lengths: 1G BSCCO tapes with silver matrix and 2G YBCO coated conductors. In particular, 2G HTS large current density even in external magnetic fields being several times greater as compared to copper [1, 2]. This allows a very compact device with a significant reduction in volume and weight. The present contribution discusses the achievements of this recent development in terms of the environmental impact over the entire life-cycle of the product, using the Life Cycle Assessment (LCA) methodology. This is one of the first applications of LCA to HTS transformers because they are innovative prototypes, still at a research and development stage. CESI RICERCA, in the frame of a public interest energy research project supported by the Italian Ministry for Economical Development carried out the comparative evaluation according to ISO 14040 Standards [3-6]. The goal was the search of critical issues and the identification of the most environmental-friendly solution among transformers with 1G and 2G HTS windings and conventional transformers, designed for 150 kV/20 kV substations with a nominal rating of 25 MVA.

TECHNICAL CHARACTERISTICS OF THE TRANSFORMERS

The HTS transformers were designed, using a methodology reported in [7] by changing the winding height and the turn voltage for two different configurations at the operating temperature T_{op}=66 K. When the best solution for HTS transformer in BSCCO was obtained, the same criteria were used to design the YBCO transformer, attaining identical efficiency value of 99.73%. Fig. 1 shows the dimensional comparison of the three different types of transformers. The proposed cooling solution is shown in Fig. 2: a vacuum external tank insulates the active parts, a water cooling system keeps the iron core at room temperature and a cryocooler removes the heat due to AC losses in the HTS conductor and keeps HTS windings at the liquid nitrogen...
temperature. Table 1 contains the main technical data of the HTS transformers and of conventional paper-oil insulated transformers with copper windings and same ratings.

<table>
<thead>
<tr>
<th>Tab. 1: Main technical characteristics of the transformers</th>
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<tbody>
<tr>
<td>BSICO</td>
</tr>
<tr>
<td>Rated power (MVA)</td>
</tr>
<tr>
<td>Power frequency (Hz)</td>
</tr>
<tr>
<td>Primary winding voltage (V)</td>
</tr>
<tr>
<td>Secondary winding voltage (V)</td>
</tr>
<tr>
<td>Cooling system</td>
</tr>
<tr>
<td>Connection type</td>
</tr>
<tr>
<td>Total height (mm)</td>
</tr>
<tr>
<td>Total width (mm)</td>
</tr>
<tr>
<td>Winding diameter (mm)</td>
</tr>
<tr>
<td>No-load losses (kW)</td>
</tr>
<tr>
<td>Total load-losses (kW)</td>
</tr>
<tr>
<td>Total weight (kg)</td>
</tr>
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FUNCTIONAL UNIT AND ASSUMPTIONS FOR ENVIRONMENTAL EVALUATIONS

The LCA comparison was based upon existing data on the engineering characteristics of the conventional transformers and data and engineering estimates for HTS transformers based upon past experience with systems under development. The comparison of the life-cycle environmental impacts was carried out considering the following functional unit: the transformation of a 150 kV three-phase voltage into a 20 kV voltage supplying a maximum power of 25 MVA, during an operating life of 30 years, according to the daily load curve showed in Fig. 3.

THE SYSTEM AND ITS BOUNDARIES

A “from cradle to grave” approach was adopted for comparative LCA. The schematic life-cycle of the functional unit is shown in Fig. 4.

It is composed of the following main phases:

(a) **Production** limited to raw materials acquisition and their transportation from mines to the manufacturing plants where the semi-finished products are obtained.

(b) **Installation** comprising:

- the ground digging out and the laying of the basement, for the HTS transformer cases, or the mineral oil collecting tank, for the conventional transformer and the related consumption of materials and fuels for transportation,
- the transformer transportation and installation in a HV/MV substation and related fuel consumption.

(c) **Use** including:

- energy consumption, due to the load losses of the transformer calculated applying the utilization factor of Fig. 3, and adding the contribution due to the cooling system, in the case of HTS transformers,
- maintenance of the conventional transformer, with the oil cleaning or the cooling system pumps of the HTS transformer, with the related energy and material consumption and the transportation of the technical personnel.

(d) **End-of-life management** including:

- the dismantling of the transformer and its transportation to a waste collector,
- the recycling of metals with 99% mass efficiency, (100% for silver) in a closed loop, and the mineral oil recycling by a hydrofinish process,
- the incineration of PVC, paper and pressboard recovering the energy with 21% efficiency and the land filling of porcelain, Kapton, PTFE and metal scraps,
- the grinding of fiberglass reinforced resin to be use as filler in concrete.
DATA QUALITY

The data considered in the inventory are related to the current Italian scenario and to the best present technology. The load curve is referred to ENEL Distribuzione. Data about fuel consumption for transportation and the energy necessary for the material recycling were collected from manufacturers, builders and waste industry. Model implemented in the commercial LCA software TEAM of PW&C, were used for production of raw materials, emissions to air, soil and water of the transportation, recycling and incineration processes. The releases of the metal recycling and the model of Kapton production were missing for lack of information. No cut-off criteria in terms of either mass or energy were applied to LCA data.

IMPACT ASSESSMENT

The main problems connected with electrical components life are related to atmospheric emissions and resource depletion, due to the electricity production and consumption. Therefore the impact categories chosen for the comparison were:

1. WH (Waste hazardous production)  
2. WT (Waste total production)  
3. TPE (Total primary energy consumption)  
4. EL (Electricity consumption)  
5. DRR (CML 1 Depletion of non renewable resources)  
6. GE (IPCC2 Greenhouse effect over 20 years)  
7. AA (CML Air acidification)  
8. EU (CML Eutrophication)  
9. XTX (USES 2.03 Human toxicity)  
10. OLD (WMO4 Depletion of the ozone layer average)  
11. PHF (WMO Photochemical oxidant formation)

The analysis of the environmental profiles of each transformer allows to make the following considerations:

- The load losses during the use phase are the main cause of the life-cycle environmental burden, as their compensation needs the production of the same quantity of electricity. This causes emissions and waste production, typical of the Italian energetic mix, with a contribute > 99% to the all life-cycle impacts for HTS devices. For conventional transformers this contribution is smaller owing to the higher impacts of the installation phase.

- All the impacts of transportation and installation phases represent less than 1% of the HTS transformer ecoprofiles. In the case of the conventional device, the high amount of the concrete and steel required for the oil leaking tank construction and the greater diesel oil consumption of transportation and digging equipment produce ~5% of the total PHF and EU impacts.

- The impacts due to production phase of the three transformers are less than 2% of the life-cycle impacts, except the very high contribution to the depletion of the non renewable resources: ~3200% for BSCCO and 87% for YBCO particularly due to silver use for tapes, 30% for conventional device due to copper. Moreover there is a contribution of ~28% and 15% to the Greenhouse effect for YBCO and BSCCO respectively, due to the stainless steel production. The silicon steel for core, the steel and the mineral oil production processes are the main cause of total and hazardous waste production.

- At the end-of-life management, a compensation greater than 80% of the raw material acquisition impacts and the Greenhouse effect is due to the closed-loop metal recycling and oil recycling. But the energy consumption of these operations and of the fibreglass reinforced resin grinding limits this benefit.

The result of the comparison of each phase impacts expressed in percent unit of the life-cycle values for YBCO transformer is shown in Fig. 5, while Fig. 6 contains the percent incidence of production and end-of-life management of all BSCCO materials on every impact category.

1 Centre of Environmental Science of Leiden  
2 Intergovernmental Panel on Climate Change  
3 Uniform System for Evaluation of Substances  
4 World Metrological Organization
The comparative analysis of the life-cycle environmental impacts of the transformers is reported in Fig. 6a, expressing, in percent unit of the values for the conventional transformer, the performances of the HTS transformers. The YBCO device shows the best environmental performances being its curve internal to the others for all impact categories, while the conventional transformer has the worst ecoprofile. This is mainly due to the energy losses in the use phase: the ratio between the consumptions of the conventional and BSCCO transformers is ~2.5; meanwhile, the ratio is ~5 for the conventional and YBCO transformers. The emission in air, water and soil is typical of the Italian energetic mix, where only 19.4% of electricity production comes from hydroelectric, wind and waste generation plants: CO₂ and methane are responsible for the 63% and 30% of the Greenhouse Effect, see Fig. 6b.

Because of its weight, the conventional transformer is also the worst in the production and installation phases, but the HTS transformers present higher impacts for Human Toxicity, Greenhouse Effect and Depletion of non-renewable resources in the production phase because of the high stainless steel quantity and of the silver and the oxides used in the HTS tapes.

Since Fig. 6 must be considered in the “less is better” logic, all the impact categories indicate that the HTS YBCO transformer is the most environmental-friendly solution.

**CONCLUSIONS**

A comparative LCA, with a “from cradle to grave” approach, was performed on three 25 MVA transformers for HV/LV distribution substations, with the following different manufacturing characteristics:

- a HTS transformer with first generation (1G) BSCCO tape windings,
- a HTS transformer with second generation (2G) YBCO coated conductors windings,
- a conventional paper-oil insulated transformer with copper windings.

The results of the analysis has demonstrated that the HTS YBCO transformer is the most environmental-friendly solution under all considered stress factors: this result is mainly due to its reduced energy losses in the use phase and to the quantities of raw materials used for its production, that are the lowest. Thanks to its lower weight, also its transportation and installation phase are environmentally the best. The only improvement that can be suggested is the search of a material with a lower energy consumption in production and recycling phases to replace the fibreglass reinforced resin. The conventional transformer because of its higher weight and energy losses shows the worst environmental profile: only the use of an amorphous core could reduce its energy losses, but its weight and dimension are higher.

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**REFERENCES**